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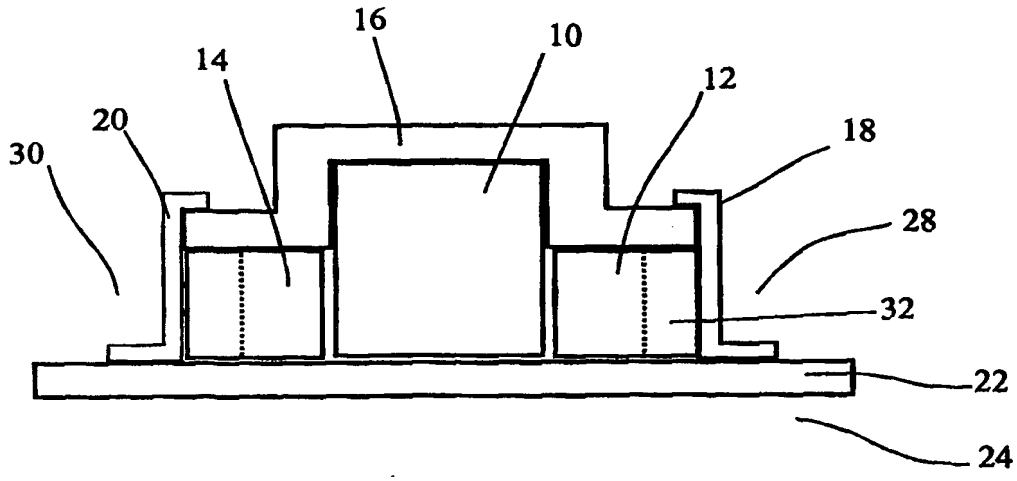

(57) Abstract

A doped substrate (12) is described for use around a ridge waveguide (10), for controlling the refractive index of the waveguide material. Instead of simply diffusing dopant in from a surface of the substrate (12) adjacent the waveguide (10), an area of the substrate is etched and dopant diffused in from a side face of the etched region (28, 30). Thus, the dopant profile is established from a horizontal direction, allowing the profile to be controlled. A simple vertically uniform doping profile (12) can thus be provided, leading to a vertically uniform current density, or an anisotropic wet etch can be applied after the initial etch to provide a profile (36) which concentrates the current density at a selected height in the substrate.

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ELECTRO OPTIC MODULATOR

TECHNICAL FIELD

This invention relates to electro optic modulators.

BACKGROUND ART

It is known to form p-i-n devices around ridge waveguide structures. A summary is shown in figure 1, where the ridge 10 is surrounded by a slab region 12, 14 on either side, together forming a single mode ridge waveguide. The device is protected with an oxide layer 16, in which openings 18, 20 are formed either side of the ridge 10. These regions are doped to form local p and n regions, thus creating a p-i-n diode across the waveguide. This can be used to manipulate the charge carrier concentration within the waveguide, thus controlling its refractive index. This can then be used to modulate a light beam passing through the waveguide. Alternatively, a n-i-n or p-i-p structure will be sufficiently conductive to provide a thermal phase modulator by controlling the refractive index through its temperature dependence.

As illustrated, the device is a silicon-on-insulator structure in which the active components are formed over an insulating oxide layer 22 on a supporting silicon substrate 24.

The dopant in this arrangement is controlled to remain in the substrate region on either side of the waveguide so that the single mode light beam does not meet a doped region. This is because dopant elements tend to act as absorption sites for the light beam, leading to signal losses and local heating.

Dopant is added to such structures in a generally well-known

manner, in which the surface of the silicon is exposed to a dopant-containing gas. Areas which are not to be doped are covered with a protective layer of SiO_2. Dopant then travels through the silicon according to the diffusion equations, which stipulate that for a constant concentration of dopant at the surface, the dopant concentration within the silicon will decline exponentially with distance, but that, as time progresses, the rate of that decline with distance will fall. Effectively, this means that the concentration at any one point will increase with time.

A difficulty in manufacturing the structure shown in figure 1 is that the dopant profile is difficult to control, as a result of the above. It tends to adopt the shape 26 shown in fig 1, in which sideways diffusion takes place at the edges of the opening in the protective SiO_2 layer. The shape which results means that the current density and current path will vary across the vertical extent of the light mode. Ideally, the current density would be controlled to maximise the overlap between the electrical current and the optical mode.

It is possible to heat treat a doped region such as to drive the dopant into the substrate. A deeper dopant profile such as this might create would be preferable per se. However, this process will tend also to spread the dopant horizontally, with the result that the doped areas would then need to be more widely separated from the waveguide. This in turn is undesirable. The wider doped areas would also lead to a less preferred current density profile.

DISCLOSURE OF INVENTION

The present invention seeks to provide an electro optic device in which the dopant profile allows a more appropriate current density profile to be established during use.

In its first aspect, the present invention provides an electro-optic

device comprising a ridge waveguide surrounded on either side by a slab substrate containing dopant, thereby to form a conductive path across the waveguide, the doped region being bounded on at least two sides by a confining layer of a material different to the material of the slab substrate.

In its second aspect, the present invention provides an electro optic device comprising a ridge waveguide surrounded on either side by a slab substrate containing dopant, thereby forming a conductive path across the waveguide, the dopant having a substantially uniform distribution in the substrate in the vertical direction.

In a third aspect, the invention provides an electro optic device comprising a ridge waveguide surrounded on either side by a slab substrate containing dopant, thereby to form a conductive path across the waveguide, the dopant having been diffused into the substrate in a substantially horizontal direction.

In a fourth aspect, the invention provides an electro optic device comprising a ridge waveguide surrounded on either side by a slab substrate containing dopant, thereby to form a conductive path across the waveguide, the dopant having been diffused into the substrate from a side surface of an etched region formed in the substrate material.

The invention also relates to a method of forming an electro optic device comprising the steps of forming a ridge waveguide on a substrate surface, etching a region of the substrate on at least one side of the waveguide and applying a dopant to a side surface of the etched region thereby to introduce the dopant into the substrate in a substantially horizontal direction.

It is possible to further etch the etched substrate region with an anisotropic wet etchant. This will leave the etched region with internally relieved sides, a profile which will be transferred to the dopant profile. This

can be used to tailor the conductive region, for example to provide a peak current density co-incident with the peak light intensity of the mode distribution.

Other preferred features of the invention will be apparent from the following description and the subsidiary claims of the specification.

BRIEF DESCRIPTION OF DRAWINGS

Embodiments of the present invention will now described, by way of example, with reference to the accompanying Figures, in which;

Figure 1 is a cross section through a known electro optic device;

Figure 2 is a cross section through an electro optic device according to a first embodiment of the present invention; and

Figure 3 is a cross section through an electro optic device according to a second embodiment of the present invention.

BEST MODE OF CARRYING OUT THE INVENTION

It should be noted that for convenience of description, terms such as "lateral", "vertical", "side", "top" etc. used in the specification refer to directions relative to a device in the orientation shown in the accompanying drawings. The terms should not, however, be interpreted as restricting the scope of the claimed invention which may in practice be used in any orientation.

Figure 1 has already been described in detail, and therefore no further description will be given here.

Figure 2 shows a first embodiment of the present invention. As in

figure 1, the device is a silicon-on-insulator device in which an oxide layer 22 lies between the active elements and an underlying silicon support 24. The ridge of the waveguide 10 is again flanked on either side by slab substrate areas 12, 14, but these are now flanked by etched regions 28, 30 formed by an anistropic, directional dry etch. A protective oxide layer 16 covers the waveguide ridge 10 and the top surfaces of the substrate material 12, 14.

The substrate regions are doped after formation of the etched regions by allowing a dopant to contact side surfaces of the etched sites. This then allows dopant to diffuse into the substrate regions from the sides, across their complete depth. This differs from the example shown in figure 1, where the dopant diffuses in from an opening on the top surface and extends sideways beneath the protective layer either side of the opening. Thus, beneath the central area of the opening in this prior art, the dopant diffuses isotropically, giving a substantially flat, horizontal surface to the dopant profile as shown in Figure 1. In contrast, the novel dopant delivery described herein gives rise to a doped volume substantially as shown at 32 (fig 2), ie one which is substantially uniform through the depth of the substrate region 12, 14. In effect, the protective oxide layer 16 and the underlying oxide layer 22 serve to confine the diffusion of the dopant vertically and thereby preserve its linear profile. This means that the current density through the pin device thus formed will be controllable. In the embodiment of figure 2, the dopant profile will be substantially uniform in the vertical direction. This arrangement will therefore give a more uniform control of refractive index in the vicinity of the light signal.

Electrical contacts 18, 20 are then provided by depositing suitable material into the etched regions 28, 30 after doping.

Figure 3 shows an alternative arrangement. This is generally similar to the embodiment of figure 2, but differs in that after etching the regions 28, 30 either side of the substrate regions 12, 14, an anisotropic wet

etchant such as KOH is applied. As shown, it is applied to both sides of the device, which is preferable. This will give the etched side of the substrate regions 12, 14 an undercut profile as shown at 34. When the dopant is applied, it will diffuse into the substrate and retain the profile of the outer surface of the etched region, thus providing a "point" 36 to the dopant profile level with the undercut. The horizontal extent of the undercut and its vertical position can be controlled by the depth of the initial isotropic etch. A deep initial etch, e.g. through to the oxide layer 22, will lead to an undercut of greater horizontal extent and a lower position of the point 36. Whereas a shallow initial etch, i.e. not through to the oxide layer 22, will lead to an undercut of smaller horizontal extent but a higher position of the point 36. This alternative arrangement thus results in a current profile which is maximised at a controllable depth in the device. A similar effect could be obtained by only applying the anisotropic wet etch to one side, but this would be more difficult to carry out.

It is known that the mode of propagation of light signals in ridge waveguides such as illustrated is one in which the peak concentration of light energy is slightly below the surface of the substrate material. Thus, by controlling the current density to be a maximum at this point, it is possible to make most efficient use of the current by matching the current profile to the light energy profile.

The doping method described herein produces doped areas which have a substantially uniform horizontal thickness through the depth of the substrate. The doped areas also extend through the depth of the substrate but do not extend substantially into the waveguiding area.

Many variations could be made to the above-described embodiments without departing from the scope of the present invention. For example, similar constructions can be used to provide n-i-n and p-i-p devices, by suitable adjustment of the dopant elements. Alternatively (or in addition), electrical contact could be provided on the top surfaces of the doped areas.

The regions 28, 30 can be left etched, subject to any necessary protective layers, or they can be filled with silicon, SiO_2, or other deposits.

CLAIMS

1. An electro optic device comprising a ridge waveguide surrounded on either side by a slab substrate containing dopant, thereby to form a conductive path across the waveguide, the dopant having a substantially uniform distribution in the substrate in the vertical direction.

2. An electro optic device comprising a ridge waveguide surrounded on either side by a slab substrate containing dopant, thereby to form a conductive path across the waveguide, the dopant having been diffused into the substrate in a substantially horizontal direction.

3. An electro-optic device comprising a ridge waveguide surrounded on either side by a slab substrate containing a doped region, thereby to form a conductive path across the waveguide, the doped region being bounded on at least two sides by a confining layer of a material different to the material of the slab substrate.

4. An electro-optic device according to claim 3 in which the ridge waveguide and the slab substrate are of like material.

5. An electro-optic device according to claim 3 or claim 4 different material is SiO_2.

6. An electro optic device comprising a ridge waveguide surrounded on either side by a slab substrate containing dopant, thereby to form a conductive path across the waveguide, the dopant having been diffused into the substrate from a side surface of an etched region formed in the substrate material.

7. An electro-optic device according to claim 6 wherein the etched regions are filled with one of silicon and SiO_2 after doping.

8. An electro-optic device according to any preceding claim in which the waveguide is of silicon.

9. An electro-optic device according to any one of the preceding claims being formed as a silicon-on-insulator device.

10. An electro-optic device according to any one of the preceding claims including contacts having an electrical connection with the doped areas, the contacts being provided on a side face of the substrate.

11. A method of forming an electro-optic device comprising the steps of forming a ridge waveguide on a substrate surface, etching a region of the substrate on at least one side of the waveguide and applying a dopant to a side surface of the etched region thereby to introduce the dopant into the substrate in a substantially horizontal direction.

12. A method according to claim 11 wherein a further etch, which is an anisotropic wet etch, is performed prior to application of the dopant to give the etched side surface an undercut profile.

13. A method according to Claim 12 in which the vertical position of the undercut profile is controlled by controlling the depth of the etched region etched on at least one side of the waveguide.

14. An electro optic device substantially as either one herein described with reference to and/or as illustrated in the accompanying figures 2 and 3.

15. A method of manufacturing an electro optic device substantially as either one herein described with reference to and/or as illustrated in the accompanying figures 2 and 3.

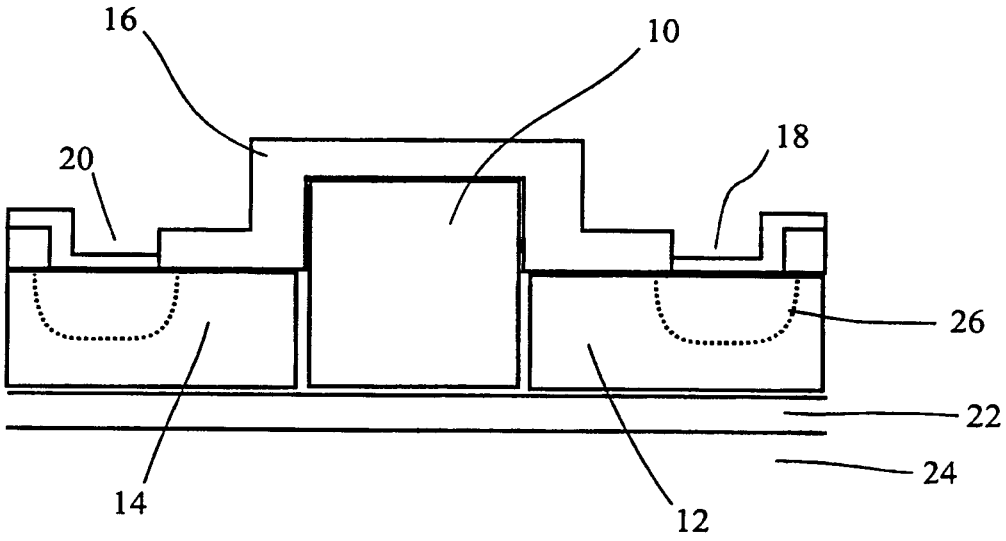

Fig 1

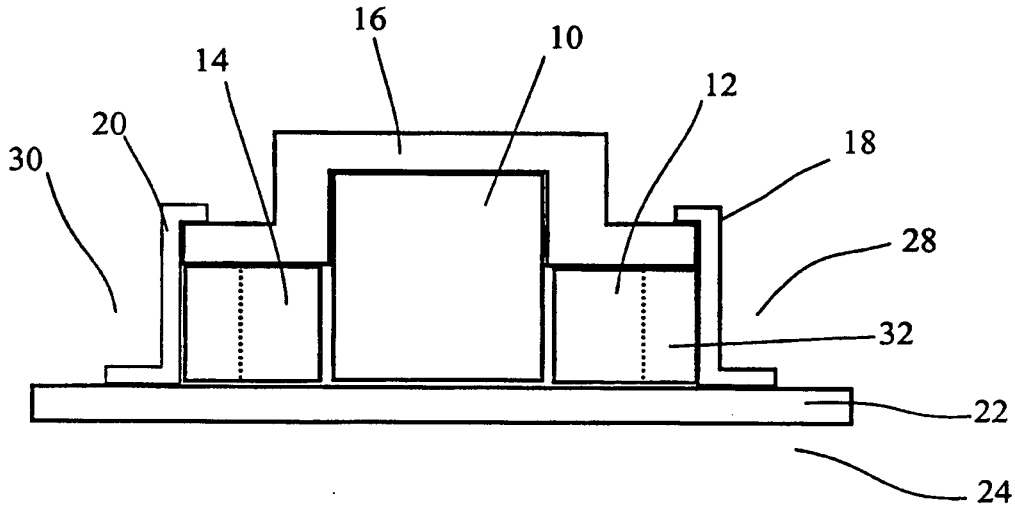

Fig 2

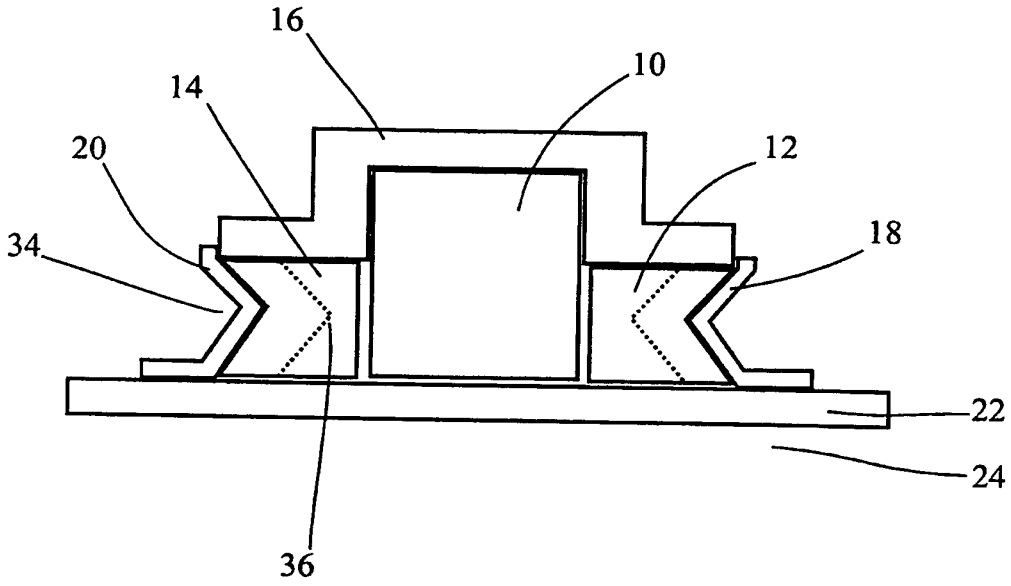

Fig 3

INTERNATIONAL SEARCH REPORT

Intern. al Application No
PCT/GB 99/02537

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G02B6/12

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G02B H01S H01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	PATENT ABSTRACTS OF JAPAN vol. 017, no. 484 (E-1426), 2 September 1993 (1993-09-02) & JP 05 121774 A (NEC CORP), 18 May 1993 (1993-05-18) abstract -& JP 05 121774 A figures 1-3	1-3,6, 11,14,15
A	US 4 865 923 A (RALSTON JOHN D ET AL) 12 September 1989 (1989-09-12) column 2, line 19 - line 31 column 3, line 59 - line 67 column 8, line 62 -column 9, line 4; claim 1	1-3,6, 11,14,15

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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INTERNATIONAL SEARCH REPORT

Information on patent family members

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